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Behaviour and strength of existing bridges with low amount of shear reinforcement

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Abstract

In the last decades, the assessment of the strength of existing structures has become a major issue in structural engineering. Prestressed concrete bridges are of particular relevance, due to the large number of these structures and to the significant changes occurred in the design approaches and traffic actions. In particular, a number of these structures built before the 1980's present insufficient amount of shear reinforcement or defective stirrup anchorage compared to current design standards. This, however, does not necessarily mean that these structures are actually unsafe and have to be retrofitted because code provisions are mostly oriented for design of new structures and their design provisions include a number of safe in-built hypotheses.

In this paper, the strength of prestressed girders with low amount of shear reinforcement or with defective anchorage is investigated by means of a test programme carried out at the Ecole Polytechnique Fédérale de Lausanne on 10 prestressed and 2 reinforced concrete girders (10 m long, 0.78 m high). The results show that if certain conditions are fulfilled, these structures can perform suitably and provide the expected strength according to plastic design approaches. For comparisons, the elastic-plastic stress fields method is used to predict the specimens' strength leading to excellent correlations between the measured-to-predicted behaviour and strength. Furthermore this approach allows a sound understanding of the various shear-carrying mechanisms developed in the girders and of the various failure modes observed.

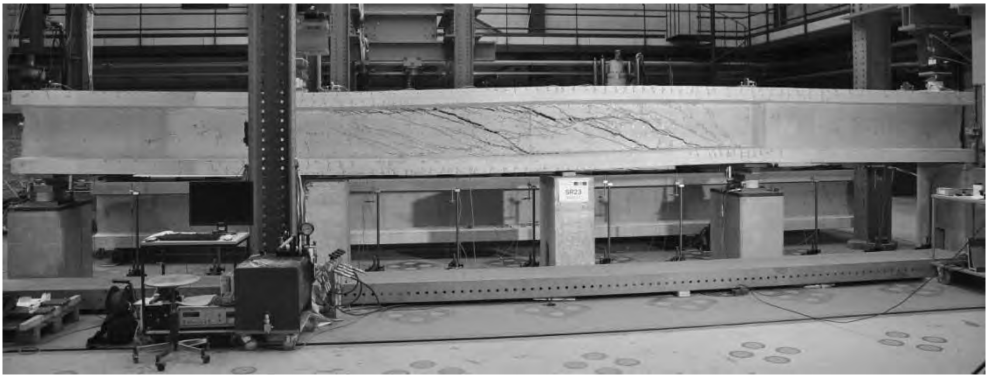

Fig. 1 Tested beam SR23 after failure

1 Introduction

During the assessment of an existing structure, especially for prestressed concrete bridges, the requirements of the current design codes can often not be fulfilled. Many existing bridges show insufficient amount of shear reinforcement or defective stirrup anchorage compared to current codes. As a consequence, more accurate procedures like the elastic-plastic stress fields approach [1, 2] are required to ensure a safe design of the structure. Furthermore the improvement of current code provisions is desired to obtain a safe and economical design for the bridge girders.

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In this research project, the influence of low amount of shear reinforcement, the insufficient anchorage of the stirrups, and the presence of beam flanges on the behaviour of a structural element is analysed. The objectives are to show that an assessment for the mentioned bridges is possible and to give the guidelines for their verification in agreement with current code approaches. To gain a better understanding of the behaviour of such structures, a test series of ten prestressed concrete girders and two reinforced concrete girders has been performed at the Ecole Polytechnique Fédérale de Lausanne EPFL.

This paper presents an overview of the test series and shows the main results of the experiments. The experimentally obtained results have been compared to predictions using the elastic-plastic stress fields approach and using current codes of practice (Eurocode 2: 2004 [3], Model Code: 2010 [4]).

2 Test program

2.1 Test setup

The twelve tested single span beams with cantilever correspond to a multi span bridge with a span of about 40 m on a scale of 3/8. According to the test setup (figure 2), the maximal bending moment is acting together with the maximal shear force likewise the support regions of multi span bridges. In the tests, the applied force on the cantilever is chosen to be always half of the force in the span of the beam. Thus, the magnitude of the shear force is constant over the whole beam and corresponds to the applied force on the cantilever.

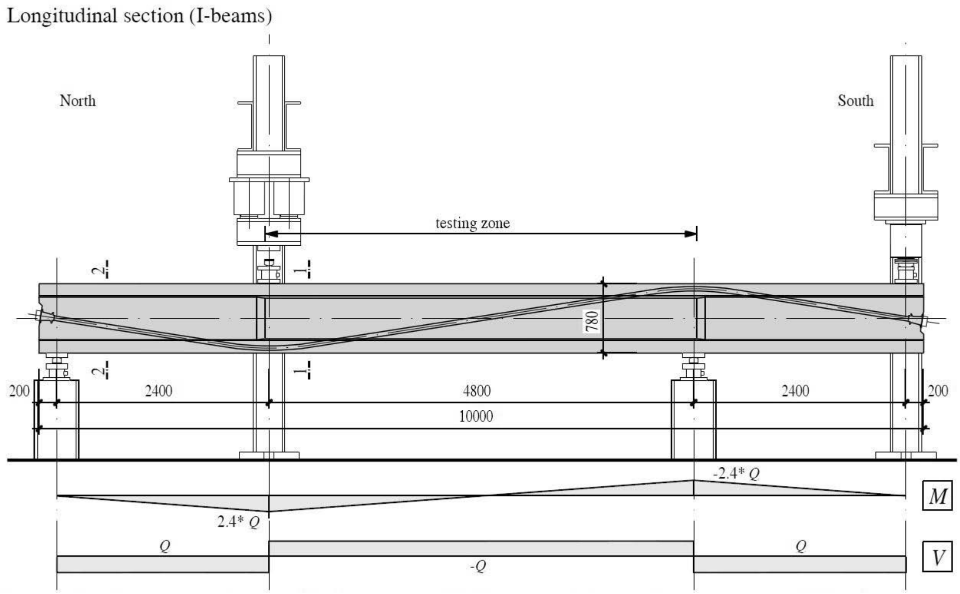

Fig. 2 Test setup: Longitudinal section with diagram of the bending moment and the shear force

Only the central part of the beam is used as test region (figure 2). The exterior parts of the beam had a larger width and amount of shear reinforcement and thus higher shear strength then the testing zone. With the conducted measurements the general behaviour of the beam is recorded on the whole length of the beam. Measurements of web deformations are limited on the testing zone.

2.2 Test specimen

2.2.1 Main parameters

The main parameters of the test series are the cross section, the amount of post-tensioning P/A, the shear reinforcement ratio ρ_w and the anchorage properties of the stirrups. The value P denotes the post-tensioning force and A the area of the cross section in the testing zone. In figure 3, the two types of cross sections are shown. The prestressing is introduced by one or two post-tensioning cables in the girder. Three beams contain open stirrups which would mean that the longitudinal reinforcement bars are not enclosed by the shear reinforcement (refer to table 1).

Table 1 Main parameters of the test series

Beam SR..	21	22	23	24	25	26	27	28	29	30	31	32
section	⌶	⌶	⌶	⌶	⌶	⌶	⌶	⌶	⌶	⌶	▯	▯
P/*A* [MPa]	2.5	2.5	2.5	2.5	5.0	5.0	5.0	-	2.5	2.5	3.0	-
ρ_w [%]	0.09	0.13	0.06	0.25	0.09	0.06	0.19	0.09	0.25	0.25	0.09	0.09
stirrup	▯	▯	▯	⊔	▯	▯	▯	▯	⊔	⊔	▯	▯

2.2.2 Geometry and material properties

The length, the height, and the web thickness in the central part of all tested beams are the same (figure 3). In the testing zone the shear reinforcement consists of stirrups or single bars with a diameter of 6 mm and a spacing between 150 mm and 300 mm. The post-tensioning consists of one or two cables VSL 6-4 in ribbed steel ducts and anchorage heads VSL-EC25. All the steel ducts are grouted with a high strength mortar after tensioning of the wires. The cable position follows the bending moment as indicated in figure 2.

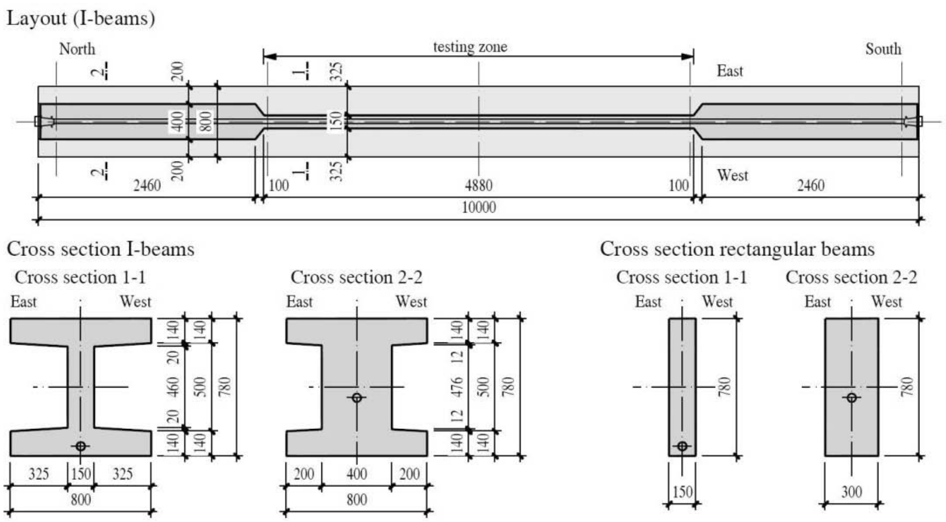

Fig. 3 Dimensions of the beams: Layout (top), cross section I-beams (bottom left) and cross section rectangular beams (bottom right)

Standard concrete without any additives and aggregates with a maximal diameter of 16 mm has been used. The concrete cylinder strength f_c at the testing day varies between 29.8 MPa and 37.8 MPa. For the beams with flanges the measured yielding strength of the shear reinforcement f_y is 580 MPa, the ultimate strength f_t is 630 MPa and the ultimate strain ε_u is 3.0 %. For the beams without flanges the yielding strength of the shear reinforcement f_y is 530 MPa, the ultimate strength f_t is 590 MPa and the ultimate strain ε_u is 5.5 %.

3 Test results

All tested beams failed in shear. Figure 4 shows the deflection under the loading point in the span versus the shear force. As expected, the larger the amount of shear reinforcement the larger the ultimate strength. The same applies to the increasing amount of post-tensioning force. The beams with flanges show a rather large deformation capacity, in spite of the lowest amount of shear reinforcement. The residual strength is between 60 and 70 % of the ultimate strength and the deformation could be increased without any big loss in this residual strength. In contrast to this observation, the beams without flanges behave more brittle and show a smaller loading capacity. After reaching the ultimate strength the beams fail suddenly with small strength afterwards.

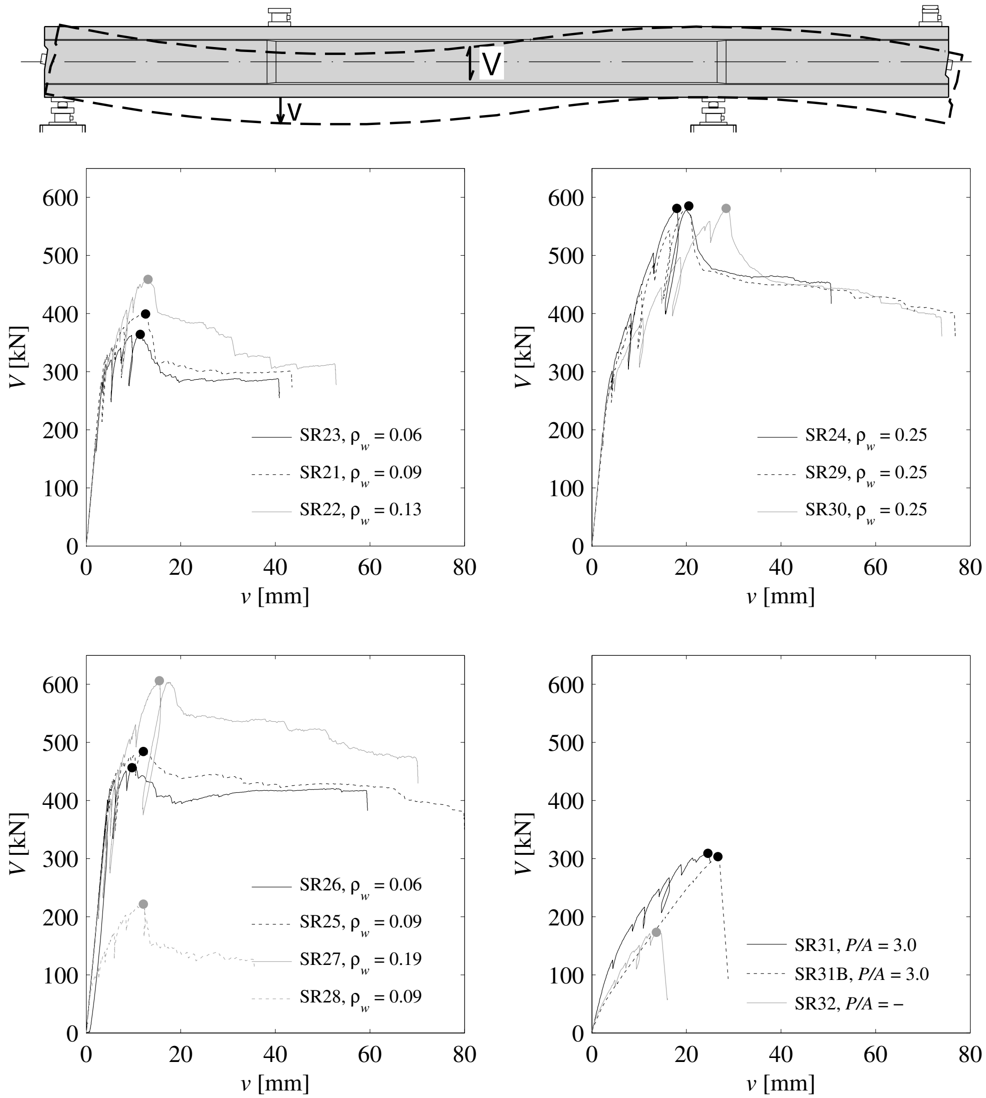

Fig. 4 Test results: scheme of the deformation (top), beams with flange and P/A = 2.50 MPa (centre left), beams with flange and open stirrups (centre right), beams with flange and P/A = 5.00 MPa or P/A = - (bottom left) and beams without flange (bottom right)

The numerical values of the ultimate strength $V_{R,test}$ are presented in table 2. It can be noted that the beam SR31 has been externally reinforced after failure and tested once again as SR31B.

4 Discussion of the test results

Before starting the test series, all beams were modelled to predict their strength and behaviour. This prediction has been done with a model using the elastic-plastic stress fields (EPSF) [2]. Table 2 and figure 5 (top left) present the resulting values. The comparison of the prediction with the test results over all the beams gives an average value $V_{R,test}/V_{R,pred}$ of 1.06 and a coefficient of variation of 0.05. The prediction of the EPSF method is thus in very good agreement with the test results.

Table 2 Resulting shear strength of the tests $V_{R,test}$ and predicted shear strength $V_{R,pred}$ using the elastic-plastic stress fields method

Beam SR..	21	22	23	24	25	26	27	28	29	30	31	31B	32
$V_{R,test}$ [kN]	399	459	364	579	484	457	606	222	585	581	309	303	173
$V_{R,pred}$ [kN]	370	430	355	560	470	445	580	220	560	540	265	265	175
$V_{R,test}/V_{R,pred}$	1.08	1.07	1.03	1.03	1.03	1.03	1.04	1.01	1.04	1.08	1.17	1.14	0.99

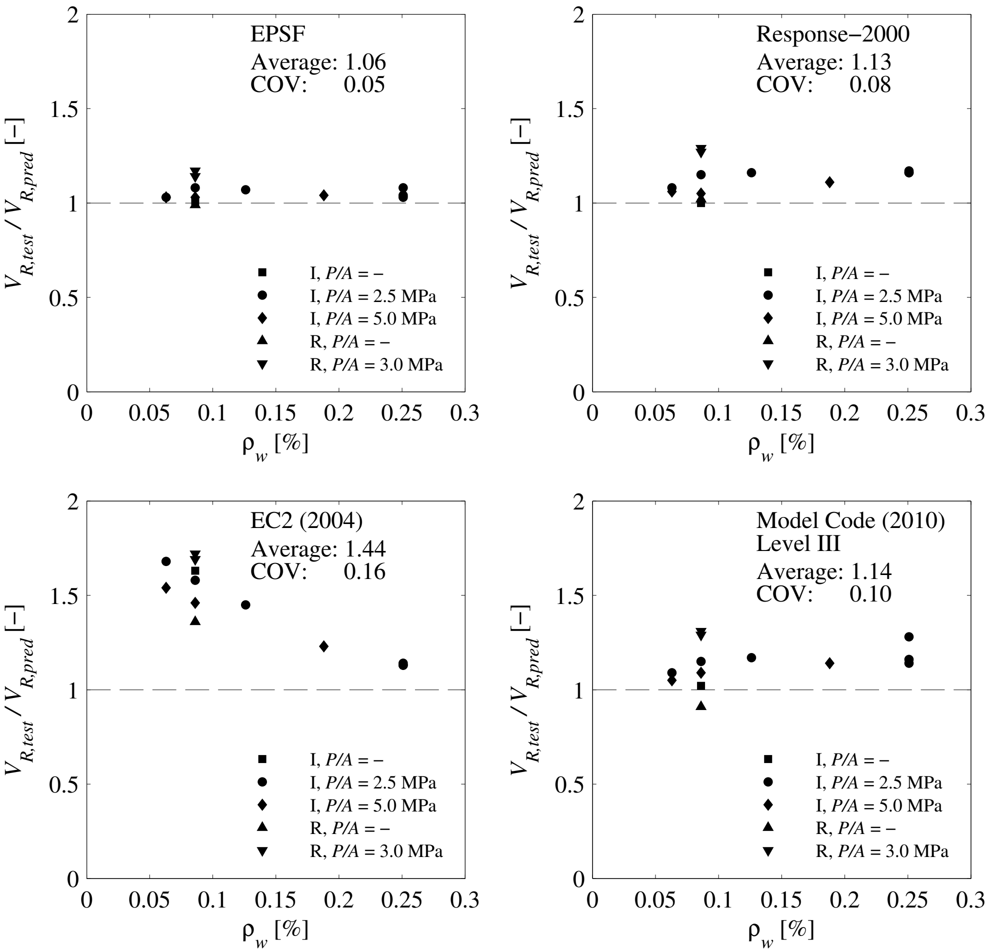

Fig. 5 Ratio of $V_{R,test}/V_{R,pred}$ for different models versus the shear reinforcement ratio: EPSF [2] (top left), Response-2000 [5] (top right), Eurocode 2 (2004) [3] (bottom left), and Model Code Level III (2010) [4] (bottom right), (I = beam with flanges, R = beam without flanges, COV = Coefficient of variation)

A comparison of the test results with the Eurocode 2 (2004) [3], the Model Code (2010) [4], and the program Response-2000 [5] is also given in figure 5. One can see that the Eurocode leads to conservative results for the tested beams and to a rather large coefficient of variation of 15 %. The Model Code (Level III) leads to less conservative results and to a coefficient of variation of 10 %. The program Response-2000 allows a sectional analysis based on the Modified Compression Field Theory [6]. With an overestimation of the ultimate shear force of 13 % the results are much better than the code predictions. The most accurate prediction is given by the EPSF method.

This comparison shows that design codes provide generally safe estimates as some shear-transfer actions are neglected (as the inclined component of the compression chord) and conservative values are given for some design parameters (angle of the compression struts, strength reduction factor of cracked concrete). A theoretical research on this topic is under work.

A more general view on the test results show that the presence of flanges is very beneficial and changes the behaviour of the whole structural element. For instance, they increased the ultimate strength of the reinforced beam without post-tensioning by 25 % (refer to specimens SR28 and SR32). Another beneficial aspect is the observed change in the deformation capacity. The beams with flanges showed large deformation capacity and residual strength whereas the beams without flanges showed a lower deformation capacity and less post-peak resistance.

5 Conclusion

This paper presents an investigation on the shear strength of prestressed reinforced concrete beams with low amount of shear reinforcement. The investigation is based on a test series of ten prestressed concrete girders and two reinforced concrete girders whose main results are presented in this paper. Its main conclusions are:

- The shear strength of the beams increase with larger amount of shear reinforcement and with increasing post-tensioning force.
- The shear strength of girders with flanges is significantly larger than the shear strength of beams without flanges, keeping the shear reinforcement ratio constant.
- The flanges provide rather large deformation capacity and residual resistance after peak load.
- Design codes generally provide safe estimates for the tested girders.
- The elastic-plastic stress fields method is applicable for structural elements like the tested beams and led to the best prediction.

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